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Effect of cutting parameters on cutting force and surface roughness during finish hard turning AISI52100 grade steel

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Abstract

The present work is an attempt to develop a force prediction model during finish machining of EN31 steel (equivalent to AISI 52100 steel) hardened to 60±2 HRC using hone edge uncoated CBN tool and to analyze the combination of the machining parameters for better performance within a selected range of machining parameters. A full factorial design of experiments procedure was used to develop the force and surface roughness regression models, within the range of parameters selected. The regression models developed show that the dependence of the cutting forces i.e. cutting, radial and axial forces and surface roughness on machining parameters are significant, hence they could be used for making predictions for the forces and surface roughness. The predictions from the developed models were compared with the measured force and surface roughness values. To test the quality of fit of data, the ANOVA analysis was undertaken. The favourable range of the machining parameter values is proposed for energy efficient machining.

Keywords: Hard tuning; regression analysis; cutting forces; surface roughness.

1. Introduction

Hard turning is performed on hardened steels in the 45 to 68 Rockwell hardness range using a variety of tool materials preferably CBN. Although grinding is known to produce good surface finish at relatively high feed rates, hard turning can produce as good or better surface finish at significantly higher material removal rates without using coolant or special tooling (Fig.1). Although the process uses small depths of cut and feed rates, estimates of reduced machining time are as high as 60% for conventional hard turning as compared to grinding [1]. A single setup may be enough for multiple hard turning operations rather than multiple grinding setups. This also contributes to high accuracy achieved by hard turning. Cutting forces and surface produced on the workpiece are greatly influenced by the cutting parameters chosen. Cutting forces on the tool and surface roughness produced during finish hard turning of the workpiece may be used to evaluate the performance of the process within the selected range of cutting parameters.

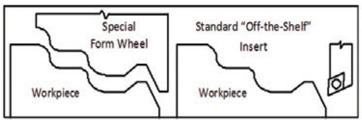

Fig.1: Grinding versus hard turning [2]

Nomenclature

v	Cutting speed in (m/min.)
f	Feed (mm/rev.)
d	Depth of cut (mm)
Fx	Axial force (N)
Fy	Radial force (N)
Fz	Cutting force (N)
Ra	Surface roughness (microns)

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Cutting forces and surface finish produced during hard turning were analyzed by many researchers. Generally the radial component of tool force is found to be the most dominant one [3-7] in finish hard turning where the depth of cut remains smaller than the nose radius of the tool. This makes the process different from the conventional turning where radial force is only around 0.3–0.5 time of the cutting force. So, the radial force cannot be neglected during finish hard turning in characterizing the static and dynamic behaviour of such machining system. However it has been seen that during hard turning with variable hone edge radius tool, the tangential force becomes highest thus increasing efficiency of cut [8].

Many researchers observed higher cutting forces during hard turning at low cutting speeds due to low temperature and built up edge (BUE) formation. The forces reduced with increase in cutting speed, which might be due to thermal softening of the work piece material due to higher cutting temperature at high speeds [9, 10]. An ANOVA [10] showed that the feed rate had considerable effect on cutting force but for thrust force, it was negligible. Another study [11] showed the increase in cutting forces with increase in feed, depth of cut and nose radius. Similar results were observed by others [12] showing influence of depth of cut on machining forces. Researchers, during hard turning of MDN 250 steels using coated ceramic tool, examined the influence of cutting parameters on cutting forces and surface roughness for speeds up to 144 m/min. [13]. It was observed that cutting speed did not influence forces significantly but feed force was affected by depth of cut. Also, the thrust and cutting forces were significantly affected by feed rate and depth of cut both.

It was observed that during finish hard turning using conventional tool geometry, the radial force component was dominant rather than the tangential force. As the cutting conditions in hard turning are fairly different from those in conventional material turning i.e. with low depth of cut and feed, this nature of forces requires a careful study. Estimation of forces may prove vital for prediction of process performance as inappropriate selection of cutting parameters may become detrimental for the tool and the process as a whole, due to the higher tool force generation and deteriorated surface finish.

2. Present work

Present work is an attempt to examine the effect of cutting parameters on the cutting forces and surface roughness produced. The turning of hardened EN31bearing steel (60±2 HRc) which is equivalent to AISI52100 was performed on a stiff heavy duty lathe (Make: HMT). CBN insert (Make: Seco, type TNGA160408 S01525) of chamfered edge geometry was used on Seco tool holder (type PTGNR 2020 K16). A piezoelectric lathe tool dynamometer (make: Kistler, model no 9257 BA) along with a charge amplifier (type 5233A) was used to measure the tool forces. The process surface roughness (Ra values), produced was measured using a portable surface analyzer in the direction parallel to work piece axis. The range of cutting parameters selected is shown in table 1. Three levels of speed, feed and depth of cuts were selected which are suitable for finish hard turning (Table1). The three forces and surface roughness were measured for all 27 experiments as per the full factorial design of experiment.

Table 1: Cutting parameters and their chosen levels

Level	Cutting speed ‘v’ [m/min.]	Feed ‘f’ [mm/rev.]	Depth of cut ‘d’ [mm]
Low	167	0.075	0.1
Medium	204	0.113	0.15
high	261	0.15	0.2

Table 2: Experimentation and measured responses

S. N.	V (m /min.)	f (mm/ rev.)	d (mm)	Fx (N)	Fz (N)	Fy (N)	Ra (µm)
1	167	0.075	0.1	17.25	32.63	51.1	2.83
2	167	0.075	0.15	21.6	45	55	3.35
3	167	0.075	0.2	51.5	74.5	111.35	6.19
4	167	0.113	0.1	19.72	39.1	60.68	1.47
5	167	0.113	0.15	23.8	54.55	64.7	2.72
6	167	0.113	0.2	56.4	80.55	154.8	2.47
7	167	0.15	0.1	23.3	53.9	69.5	1.97
8	167	0.15	0.15	27.84	69.3	75.4	2.3
9	167	0.15	0.2	63.7	103	178.6	2.05
10	204	0.075	0.1	18.45	32.6	53.4	1.37
11	204	0.075	0.15	20.66	48.5	54	2.49
12	204	0.075	0.2	57.5	79.3	134	3.83
13	204	0.113	0.1	21	44.5	61.3	1.3
14	204	0.113	0.15	22.4	53.7	60.8	2.26
15	204	0.113	0.2	62.4	86	165	2.28
16	204	0.15	0.1	22.9	51.9	69.4	1.89
17	204	0.15	0.15	24.72	63.6	66.8	2.56
18	204	0.15	0.2	63.9	98.7	185.25	1.95
19	261.1	0.075	0.1	19.4	36.5	54	1.11
20	261.1	0.075	0.15	*38.8*	*48.5*	*121.4*	*2.47*
21	261.1	0.075	0.2	50.12	58.6	138.1	5.01
22	261.1	0.113	0.1	23	39.86	70.4	1.23
23	261.1	0.113	0.15	41.9	61.5	142.7	1.95
24	261.1	0.113	0.2	59.6	83.2	166.2	1.92
25	261.1	0.15	0.1	25.24	51.84	76.74	1.38
26	261.1	0.15	0.15	46.6	87.1	157	1.43
27	261.1	0.15	0.2	66.72	111.09	184.8	1.83

3. Results and discussion

The regression analysis of the data was undertaken using *Datafit* and ANOVA was done using *Design expert* software to test the quality of fit for the data. To deal with singularities, the technique used in *DataFit* is *Singular Value Decomposition* because of its exceptional ability to handle singular matrices common in least squares solutions.

Effect of machining parameters on the forces and the surface roughness produced were analyzed using surface response method. Also, the measured response data trends were analyzed to propose the conditions for most energy efficient cut with regards to the forces produced.

3.1. ANOVA of the Force and Surface Roughness data.

The ANOVA results for axial force (Fx) data (Table 3) showed that the selected full factorial model was significant. Depth of cut was the most significant parameter having maximum contribution as also concluded by [12]. Cutting speed, feed and interaction of speed and depth of cut were other parameters which affected the axial force significantly but contributed far less than the depth of cut.

Similary the *ANOVA* anlysis for full factorial models of cutting and radial force (Fz and Fy) was also undertaken (Table 4 and Table 5). The ANOVA results showed that the models were significant for radial force and cutting force. For the cutting force (Fz) the depth of cut was the most significant parameter followed by feed as also reported by [13]. Radial force was also most affected by the depth of cut followed by speed and feed. Also, the Interaction term of speed and depth of cut of the model showed significance but had a smaller contribution as compared to speed and feed and much smaller than the contribution of depth of cut.

Table 3: ANOVA of data for axial force Fx

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	%C
Model	8205.12	18	455.84	308.13	< 0.0001	100
v	287.78	2	143.89	97.26	< 0.0001	3.62
f	269.43	2	134.72	91.06	< 0.0001	3.39
d	7119.00	2	3559.5	2406.1	< 0.0001	89.7
v.f	22.50	4	5.62	3.80	0.0511	0.14
v.d	468.67	4	117.17	79.20	< 0.0001	2.95
f.d	37.75	4	9.44	6.38	0.0131	0.23
Residual	11.84	8	1.48			
Cor Total	8216.96	26				

Table 4: ANOVA of data for cutting force Fz

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	%C
Model	12467.64	18	692.65	24.02	< 0.0001	100
v	39.77	2	19.88	0.69	0.5293	0.33
f	3117.9	2	1558.95	54.06	< 0.0001	25.63
d	8706.25	2	4353.13	150.9	< 0.0001	71.56
v.f	252.07	4	63.02	2.19	0.1611	1.04
v.d	181.47	4	45.37	1.57	0.2710	0.74
f.d	170.18	4	42.55	1.48	0.2959	0.70
Residual	230.70	8	28.84			
Cor Total	12698.33	26				

Table 5: ANOVA of data for radial force Fy

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	%C
Model	61688.6	18	3427.14	129.9	< 0.0001	100
v	5680.6	2	2840.32	107.7	< 0.0001	9.86
f	4769.9	2	2384.94	90.4	< 0.0001	8.28
d	43090.8	2	21545.39	816.9	< 0.0001	74.8
v.f	78.7	4	19.69	0.75	0.5870	0.07
v.d	6859.6	4	1714.89	65.0	< 0.0001	5.95
f.d	1209.0	4	302.25	11.5	0.0021	1.05
Residual	210.99	8	26.37			
Cor Total	61899.6	26				

Table 6: ANOVA of data for surface roughness Ra

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	%C
Model	33.32	18	1.85	18.34	0.0001	100
v	3.01	2	1.50	14.91	0.0020	10.95
f	9.25	2	4.62	45.81	< 0.0001	33.65
d	9.38	2	4.69	46.47	< 0.0001	34.13
v.f	2.17	4	0.54	5.37	0.0212	3.94
v.d	0.44	4	0.11	1.10	0.4208	0.81
f.d	9.08	4	2.27	22.49	0.0002	16.52
Residual	0.81	8	0.10			
Cor Total	34.12	26				

The model for surface roughness (Table 6) was also found '*significant'*. Depth of cut, feed and their interaction were found to be highest contributors for the selected range of cutting parameters.

3.2. Regression analysis

Cutting conditions and responses in terms of forces and surface finish observed during various experiments, formed the input to the software. A regression equation was developed for each desired output. The machining conditions from the validation set were given to the regression equations as inputs and the equations, in turn provided the predictions for the different outputs (e.g. the cutting force, axial force, radial force and surface roughness).

The regression equations, for cutting, feed and radial forces as well as the surface roughness were obtained by fitting a second order model to analyze the significant machining parameters for various cutting forces and surface roughness.

For feed force F_x, the regression equation formed is:-

$$Fx = 9.065\times10^{-4}v^2 + 27.21f^2 + 4121.33d^2 + 0.35vf$$
$$+838.66fd - 0.145dv - 0.33v - 102.79f - 920.84d + 95.93 \qquad (1)$$

For radial force $F_{y,}$ the regression equation is:-

$$Fy = 4.49\times10^{-3}v^2 - 2111.51f^2 + 8644.88d^2 + 0.124vf$$
$$+4804.17fd - 0.73dv - 1.7v + 159.11f - 2343.45d + 301.8 \qquad (2)$$

For cutting force F_z, the regression equation is-

$$Fz = 2.01\times10^{-4}v^2 + 2519.52f^2 + 2094.89d^2 + 1.75vf$$
$$+1974.16fd - 0.3dv - 0.21v - 884.08f - 351.63d + 99.11 \quad (3)$$

The regression equation for surface roughness Ra (μm) is-

$$Ra = 1.34\times10^{-4}v^2 + 421.19f^2 - 21.78d^2 + 7.35\times10^{-2}vf$$
$$-406.34fd + 2.71\times10^{-2}dv - 8.05\times10^{-2}v - 65.98f + 61.07d + 10.23 \quad (4)$$

Fig.2-5 show the comparison between measured and predicted values for various forces and surface roughness in terms of percentage error in predictions. The maximum error in prediction of axial force Fx was found to be around 25% for experiment no. 14, while for most of the other experiments it was below 10% (Fig.2). For radial force Fy, the maximum error in predictions at two data points (exp. No. 14 and 17) was quite high respectively (Fig.3). This might be due to material in homogeneity or some experimental error. For most of other data points the error was below 15%. For cutting force Fz (Fig. 4) the maximum error in prediction was around 16% for experiment no. 21, around 13.5% for experiment no. 17 and 25 and around 11% for experiment no.12 and 13. For the rest of experiments the error is well below 10%.

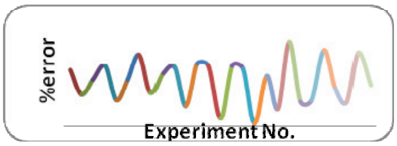


Fig.2 : % Error in predictions of axial force (Fx)

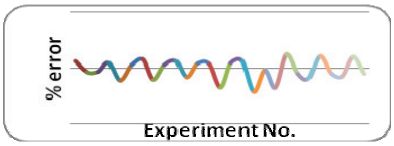


Fig.3: % Error in predictions of radial force (Fy)

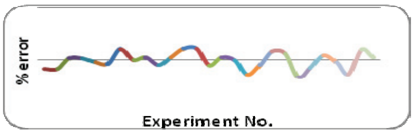


Fig.4: % Error in predictions of cutting force (Fz)

Surface roughness, when modeled with second order fit, generated high error in predictions due to abrupt nature of measured values used to develop model (Fig.5). This abrupt nature may be due to inhomogeneity of material and variation in hardness values at different locations in workpiece. The maximum error produced in prediction of various forces may also be the result of the same.

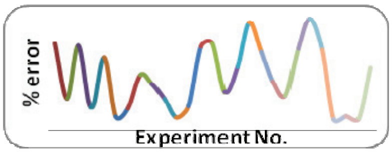


Fig.5: % error in predictions of surface roughness (Ra)

3.3. Effect of cutting parameters on the forces

To fine tune the process for the most efficient cutting within the selected range of cutting parameters, it is important to understand the effect of cutting parameters on the tool forces and surface roughness. The regression equations, discussed in previous section, were used to plot the response surface graphs for various force components and surface roughness produced. The axial forces (Fx) was found increasing with increase in depth of cut but it did not have much effect of cutting speed or feed as it is evident from figures 6a, b and c.

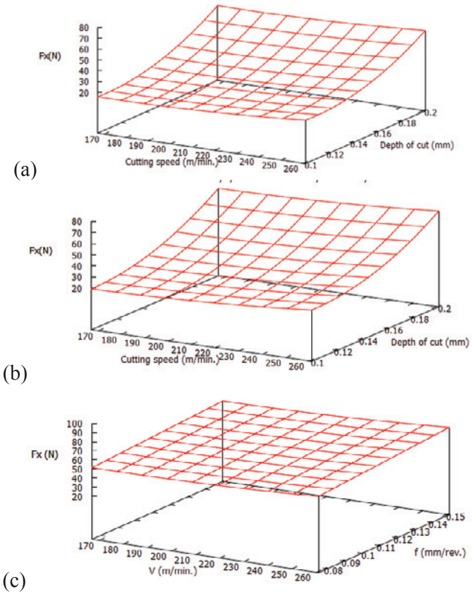


Fig. 6: Variation in axial force Fx (a) at f = 0.075 mm/rev (b) at f = 0.15 mm/rev. (c) at d = 0.2 mm

Radial force (Fy) also increased with increase in depth of cut (fig 7a and 7b). At lower feed it increased with increase in speed (fig. 7a), but at higher feed and depth of cut first there was minor reduction in the radial force and then again it increased a bit (fig. 7b). The trend is much clearer in the fig. 7c. This might be due to the fact that at high depth of cut and feed the workpiece becomes sufficiently thermally softened so that the further increase in cutting speed ceases to have an effect on the process. This may occur within certain critical range of cutting speed, which in present case falls between 170 m/min to 220 m/min. as evident from figures 6 and 7.

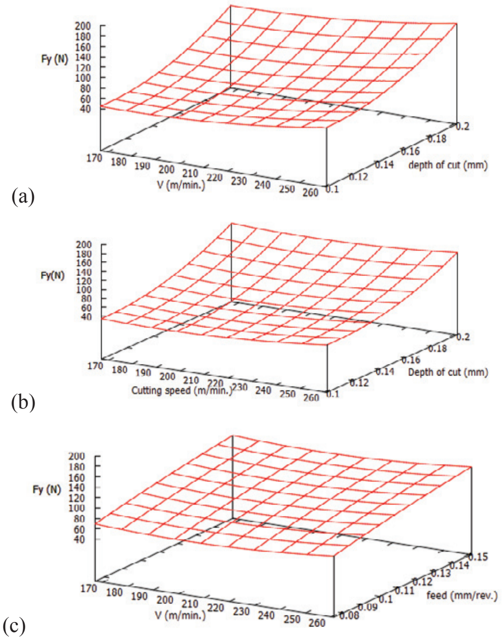


Figure7: Variation in radial force Fy (a) at f = 0.075 mm/rev (b) at f = 0.15 mm/rev. (c) at d = 0.2 mm

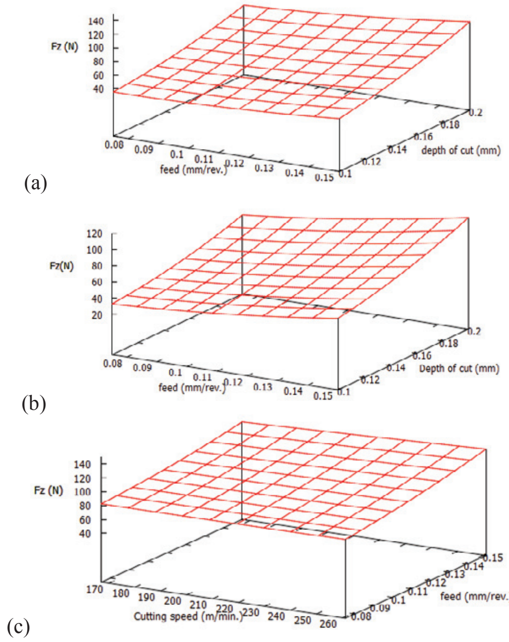


Figure8: Variation in cutting force Fz (a) at v = 167 m/min. (b) at v = 261 m/min. (c) at d = 0.2 mm

Cutting force component (Fz) increased with increase in feed and depth of cut (fig 8a and 8b). But it showed indifference with respect to cutting speed in the chosen range of machining parameters (fig 8c). This might be due to the fact that at high feed and speed the work piece material gets thermally softened and thus becoming more machinable.

3.4. Effect of cutting parameters on surface roughness

Figures 9a, b and c show the variation in surface roughness with cutting parameters. The surface roughness increased with increase in depth of cut for most of the feed values in range. But it first decreased and then increased with increase in feed for low depth of cut. While, for high depth of cut in the selected range, the surface roughness decreased with increase in feed (fig. 9a and 9b).

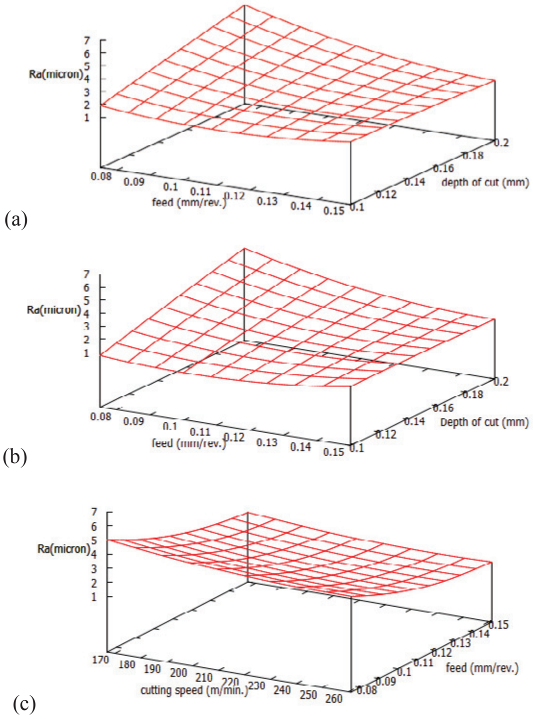


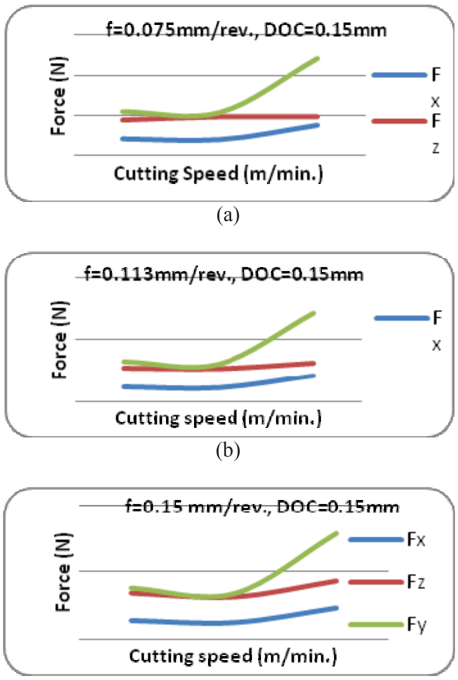
Fig. 9: Variation in Surface roughness (a) at v= = 167 m/min. (b) at v= 261m/min (c) at d = 0.2 mm

Fig. 9c show that surface roughness in the direction of turning reduced with increase in cutting speed but it was again evident that the roughness value decreased with increase in feed. The reason might be the ploughing of material at low feed. The uncut chip thickness would be very small due to small feed that might give rise to the ploughing instead of cutting at low feeds, thus producing higher surface roughness. As the feed increases, the ploughing effect reduces thus producing better surface.

3.5. Conditions for efficient cutting

Fig.10 and Fig.11 helped to observe the cases when the cutting force values were nearly similar to radial force. These were the cases for most efficient cut as it showed that the more of the power was being utilized in cutting than holding the tool in transverse direction. Figures 10a, b and c depict that the cutting might be most efficient with low and moderate cutting speed in the range selected and moderate depth of cut.

Figure 11 also shows that with speed and depth of cut being at moderate values in the selected range, the most efficient cut can be achieved for nearly all feeds selected in the range. It may be concluded that to achieve energy efficient machining, relatively lower to moderate speeds and medium depth of cut of the selected parameter range should be used.



(a)

(b)

(c)

Fig.10. Variation in forces with cutting speed for d=0.15mm (a) f=0.075mm/rev (b) f=0.113 mm/rev. (c) f=0.15 mm/rev.

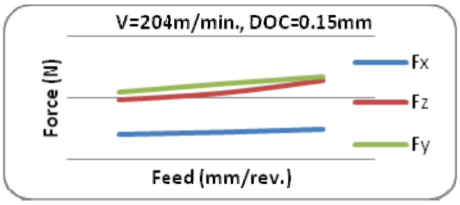


Fig. 11: Variation in forces with feed at medium speed and depth of cut

4. Conclusions

Depth of cut was found to be the most influential parameter affecting the three cutting forces followed by the feed. Cutting speed was least significant in case of axial and radial force models but was not significant for the regression model of cutting force. For the surface roughness predictions, the model developed from the analysis was found insignificant. The response surface analysis showed that forces first decreased and then increased with increase in cutting speed. It showed a critical range of cutting speed when thermal softening might have occurred that caused reduction in the forces generated. The most energy efficient cut can be achieved for relatively lower and moderate cutting speeds with moderate depth of cut in the range of parameters selected for nearly all feed values selected in the range.

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